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(54) Determining pore pressure while drilling a borehole

(57) Pore pressure  $P_{\text{pore}}$  of a subsurface formation is determined, while drilling a borehole, by measuring formation strength FS, resistivity RES and natural gamma ray activity GR.

The measurement FS includes contributions of clay volume  $V_{\text{cl}}$ , non-clay mineral strength, and a porosity, the measurement RES includes contributions from a porosity, non-clay mineral volume  $V_{\text{silt}}$  and pore fluid conductivity and the measurement GR includes contributions from clay and non-clay mineral, and the sum of  $V_{\text{cl}}$ ,  $V_{\text{silt}}$  and  $\Phi_{\text{eff}}$  is 1.

The contribution to the measurement of clay volume  $V_{\text{cl}}$ , non-clay mineral volume  $V_{\text{silt}}$ , clay porosity  $\Phi_{\text{clay}}$  and effective porosity  $\Phi_{\text{eff}}$  are derived for the formation being drilled, the clay porosity  $\Phi_{\text{clay}}$  and effective porosity  $\Phi_{\text{eff}}$  being related by  $\Phi_{\text{eff}} = \Phi_{\text{clay}}(1 - V_{\text{silt}})$ .

The pore pressure  $P_{\text{pore}}$  is derived from the relationship

$$\Phi_{\text{eff}} = \Phi_{\text{clay}}(0)[1 - V_{\text{silt}}(Z)]\exp[-aP_{\text{pore}}(Z)],$$

wherein

$$a = \frac{b}{(\rho_b - \rho_w)g} \quad \text{and}$$

$b =$  compaction coefficient at depth of interest

$\rho_b =$  density of shale

$\rho_w =$  density of pore fluid

$g =$  gravitational acceleration,  $9.81 \text{ ms}^{-2}$

$\Phi_{\text{eff}} =$  effective porosity

$\Phi_{\text{clay}} =$  clay porosity at zero depth of burial

$V_{\text{silt}} =$  volume of non-clay mineral (silt) at depth of interest.

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## PORE PRESSURE EVALUATION

The present invention relates to a method of formation evaluation for use in drilling hydrocarbon wells or the like in underground formations. In particular, the method provides a means for evaluating formation pore pressure from volumetric properties such as porosity in shale formations.

In the rotary drilling of hydrocarbon wells, drilling fluid or "mud" is circulated into the well through the drill string and returns to the surface via the annulus between the drill string and the borehole wall, bringing any rock cuttings with it. The mud also serves to exert a hydrostatic pressure on the formation to provide physical stability to the borehole and to balance any pressurised fluids in the formation being drilled so as to prevent their influx into the borehole. This latter function is important for well safety since if the formation fluid is a gas, the effect of an influx into the mud will be to reduce its density and hence the hydrostatic pressure exerted on the formation. This in turn will allow more fluid to flow into the well further reducing the density of the mud and if remedial action is not taken sufficiently quickly a blowout can occur. However, it is also undesirable to exert too high a hydrostatic pressure on the formation since this can cause fracturing and formation damage due to fluid loss into the formation which is detrimental to the ability to produce hydrocarbons such as oil.

As will be appreciated from above, it is generally desirable to maintain the mud density such that the hydrostatic pressure balances the pressure of the fluids in the formation. Consequently, it is desirable to be able to evaluate this pressure, known as "pore pressure" while drilling is being conducted such that the density of the mud can be controlled continuously in an appropriate manner. Previously proposed methods of evaluating pore pressure, such as those described in US 4,833,914 and US 4,949,575 (incorporated herein by reference) rely on measurements made during drilling using MWD technology and formation properties from formation evaluation while drilling or wireline logs. The measurements are interpreted to obtain a volumetric evaluation of the formation in the manner known as "GLOBAL" and described in US 4,338,664 which includes the porosity of the formation of interest since this is required to derive the pore pressure. The basic relationship used in this prior method to derive the effective porosity  $\Phi_{eff}$  of the formation is:

$$\Phi_{eff} = \Phi_{max} (1 - V_{clay})^2 \quad (1)$$

where  $\Phi_{max}$  is the porosity of sand with no clay present and  $V_{clay}$  is the volume fraction of wet clay in the formation.

This interpretation relies on a model of a shaley sand to interpret the measurements. It is an object of the present invention to provide a method based on an alternative model so as to allow evaluation in cases where the prior technique is less appropriate. In the present invention, the model underlying the method is one of a shale having a proportion of silt (non-clay) material and the effective porosity is given by the relationship:

$$\Phi_{eff} = \Phi_{clay}(1 - V_{silt}) \quad (2)$$

where  $\Phi_{clay}$  is the effective porosity of 100% clay at the depth or effective pressure of interest and  $V_{silt}$  is the volume fraction of non-clay materials.

In its broadest aspect, the present invention provides a method for determining the volumetric composition of a shale from its measured resistivity, wherein the measured resistivity  $RES$  is integrated according to the relationship:

$$\frac{1}{\rho_{shale}} = \sigma_{shale} = \sigma_{fluid} \Phi_{clay}^m (1 - V_{silt})^{1.5}$$

wherein  $\rho_{shale}$  is the shale resistivity,  $\sigma_{shale}$  is shale conductivity,  $\sigma_{fluid}$  is the pore fluid conductivity,  $m$  is the power law exponent,  $V_{silt}$  is the volume fraction of non-clay mineral,  $\Phi_{clay}$  is the effective porosity of 100% clay at the effective pressure of interest and is related to the effective porosity of the shale by the relationship:

$$\Phi_{eff} = \Phi_{clay}(1 - V_{silt})$$

In accordance with an embodiment of the present invention, there is provided a method of determining the pore pressure  $P_{pore}$  of a subsurface formation while drilling a borehole, comprising measuring the formation strength  $FS$ , the resistivity  $RES$ , and the natural gamma ray radioactivity  $GR$  so as to derive the contribution to the measurements of clay volume  $V_{cl}$ , non-clay mineral volume  $V_{silt}$ , clay porosity  $\Phi_{clay}$  and effective porosity  $\Phi_{eff}$  for the formation being drilled, wherein the clay porosity  $\Phi_{clay}$  and the effective porosity  $\Phi_{eff}$  are related according to the relationship  $\Phi_{eff} = \Phi_{clay}(1 - V_{silt})$  and wherein the measurement  $FS$  includes contributions of clay volume  $V_{cl}$ , non-clay mineral strength, and a porosity, the measurement  $RES$  includes contributions from a porosity, non-clay mineral volume  $V_{silt}$  and pore fluid conductivity and the measurement  $GR$  includes contributions from clay and non-clay mineral, and the sum of  $V_{cl}$ ,  $V_{silt}$  and  $\Phi_{eff}$  being 1, the pore pressure  $P_{pore}$  being derived from the relationship

$$\Phi_{eff} = \Phi_{clay}(0)[1 - V_{silt}(Z)]\exp[-aP_{pore}(Z)],$$

wherein  $a = \frac{b}{(\rho_b - \rho_w)g}$  and

$b$  = compaction coefficient at depth of interest

$\rho_b$  = density of shale

$\rho_w$  = density of pore fluid

$g$  = gravitational acceleration,  $9.81 \text{ ms}^{-2}$

$\Phi_{eff}$  = effective porosity

$\Phi_{clay}$  = clay porosity at zero depth of burial

$V_{silt}$  = volume of non-clay mineral (silt) at depth of interest.

The method according to the present invention is applicable to cases where the pore pressure or overpressure is related to the porosity of the formation being drilled.

Porosity is typically obtained from a nuclear log interpretation or optionally a resistivity log interpretation. Other suitable measurements typically include neutron porosity and total density.

In the present method, each measurement made of the formation is related to the constitution of the formation by an equation, often known as a tool response equation, which expresses the measurement obtained in terms of the volumetric components of the formation. The tool response equations, in combination with an equation which states that the sum of the volumes of all of the components is equal to one, are solved simultaneously by an incoherence minimisation technique to produce a volumetric analysis of the formation. The measured parameters are combined with other information which is known for the formation of interest eg compaction coefficient, typically obtained from tabulated data so as to enable the pore pressure to be determined.

The revised interpretation of shale resistivity provided by the present invention is related to the volumetric composition of the shale. The equation is based on a model of shale as a matrix of compacted clay, whose porosity is  $\Phi_{clay}$ , containing isolated spherical particles of silt:

$$\frac{1}{\rho_{shale}} = \sigma_{shale} = \sigma_{fluid} \Phi_{clay}^m (1 - V_{silt})^{1.5} \quad (3)$$

where  $\rho_{shale}$  is shale resistivity,  $\sigma_{shale}$  is shale conductivity,  $\sigma_{fluid}$  is the pore fluid conductivity and  $m$  is the power-law exponent.

The conductivity of the pore fluid is determined by first calculating its molarity which is then interpreted using tabulated ionic conductivity data and corrected for downhole temperature.

The simple method for calculation of total molarity is just to add the exchange ion molarity, calculated from *CEC* (cation exchange capacity for clay minerals) and porosity, to the deposition/equilibrium fluid molarity, and calculate conductivity on this basis. Using this route, the pore fluid molarity  $M_{pore}$  is given by:

$$M_{pore} = M_{equ} + \sum (CEC_i \cdot m_i) \cdot \rho_s \cdot \frac{1 - \Phi_{clay}}{\Phi_{clay}} \quad (4)$$

where  $M_{equ}$  is the depositional or equilibrium fluid molarity,  $CEC_i$  and  $m_i$  are respectively the *CEC* (equivalents/unit mass) and mass fraction of the *i*'th mineral in the clay matrix, and  $\rho_s$  the mean density of the solid material in the clay matrix. In practice,  $M_{equ}$  is likely to be a free parameter which must be determined from appropriate cross plots. Its effect is, in many cases, small compared to that of the *CEC* term.

A more complex but more correct route is to use the Donnan theory of equilibrium of membranes to calculate pore fluid molarity. In relatively fresh fluids, the simpler route is adequate. Either way, the conductivity of the pore fluid will be dominated by the motion of cations (since the clay contains a large number of fixed macro-anions) and the appropriate tabulated ionic conductivities which can be obtained from tests on representative samples are preferred rather than simple molar conductivities. If this data is limited, assumptions must be made about the partition of conductivity between cation and anion to obtain an estimated value.

The tabulated values are quoted for a temperature of, say,  $T_0$ , and the value for a downhole temperature  $T$  can be approximated using an activation energy term  $E_a$ , ie,

$$\sigma_{fluid}(T) = \sigma_{fluid}(T_0) \cdot \exp - \frac{E_a}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right) \quad (5)$$

The activation energy term  $E_a$  can be obtained from observing the variation in conductivity of fluid at differing temperatures and is known not to vary to any great degree over the scale of interest in this application. Consequently, a single representative value of  $E_a$  can be obtained by experiment and applied generally in a region of investigation. The downhole temperature  $T$  is often difficult to measure directly but can be inferred from a determination of the geothermal gradient obtained from wells in the same region. Since the temperature  $T$  can have a significant effect, the best estimation of  $T$  is desirable.

The only remaining unknown in the resistivity equation is the power-law exponent  $m$ . This is known to vary with clay mineralogy, but can be estimated over an interval from a cross-plot of

$$\log \frac{\sigma_{shale}}{\sigma_{fluid} \cdot (1 - V_{silt})^{1.5}} \text{ against } \log \Phi_{clay} \quad (6)$$

Any other depth-varying data, log-derived or otherwise, can be incorporated into the 'GLOBAL' processing method. For example, in addition to gamma-ray, formation strength and resistivity required for the method of the present invention and the pore pressure determination described in U.S. patent 4,949,575 the response equations for neutron porosity and gamma density can also be used and can be applied usefully to the method of the present invention. The basic response equations are respectively:

$$GR = \sum_i V_i GR_i$$

where  $GR$  is total gamma-ray response,  $V_i$  is the volume fraction of mineral  $i$  in the rock, and  $GR_i$  is the gamma-ray response of that mineral in the absence of the others (if spectral gamma-ray data is available, then a similar set of mineral based response equations can be written for each energy window recorded by the tool, e.g. K, U and Th decay, which give a more detailed set of inputs to the optimization procedure);

$$FS = FS_{ma} \left( 1 - \frac{V_{cl}}{V_{clzero}} - \frac{\Phi_{clay}}{\Phi_{clayzero}} \right)$$

where  $FS$  is formation strength (derived from MWD drilling parameters and normalized for variations in mud and pore pressures),  $FS_{ma}$  is the formation strength of the non-clay mineral,  $V_{cl}$  is the volume of wet clay in the formation,  $\Phi_{clay}$  is the clay porosity, and the quantities with 'zero' subscripts are the values of these parameters, picked from cross-plots, at which the formation strength falls to zero;

$$NPHI = \sum_i V_i \cdot PN_i$$

where  $NPHI$  is the total neutron porosity response, and  $PN_i$  and  $V_i$  are respectively the neutron porosity response and the volume fraction in the formation of the  $i$ 'th component of the formation (these components are pore fluid, the various silts and clays making up the shale, and organic matter);

$$RHOB = \sum_i V_i RHOB_i$$

where  $RHOB$  is the total density response, and  $RHOB_i$  is the density response of the  $i$ 'th component as above.

The GLOBAL method allows these and other available logs or similar data to be combined in the volumetrics determination, provided a suitable response equation exists. Logs which provide mineralogical discrimination such as spectral gamma-ray and photoelectric cross-section are particularly useful for the present method; for example, resolution of total clay into distinct clay minerals can give a better value for CEC of the rock, and hence make the resistivity equation, which is sensitive to this parameter, a more effective input in the volumetrics process. By placing a volumetric constraint on the formation responses, violation of the constraint causes the incoherence determined by GLOBAL to increase which in turn causes the minimisation to bring the volumetrical values back into the constrained levels. A continuity constraint can also be included to prevent wild fluctuations in calculated values in adjacent depths which can further improve the calculated results.

## Claims

- 1 A method of determining the pore pressure  $P_{pore}$  of a subsurface formation while drilling a borehole, comprising deriving the contribution to the measurements of clay volume  $V_{cl}$ , non-clay mineral volume  $V_{silt}$ , clay porosity  $\Phi_{clay}$  and effective porosity  $\Phi_{eff}$  for the formation being drilled, wherein the clay porosity  $\Phi_{clay}$  and the effective porosity  $\Phi_{eff}$  are related according to the relationship

$$\Phi_{eff} = \Phi_{clay}(1 - V_{silt})$$

by measuring the formation strength FS, the resistivity RES, and the natural gamma ray radioactivity GR and wherein the measurement FS includes contributions of clay volume  $V_{cl}$ , non-clay mineral strength, and a porosity, the measurement RES includes contributions from a porosity, non-clay mineral volume  $V_{silt}$  and pore fluid conductivity and the measurement GR includes contributions from clay and non-clay mineral, and the sum of  $V_{cl}$ ,  $V_{silt}$  and  $\Phi_{eff}$  being 1, the pore pressure  $P_{pore}$  being derived from the relationship

$$\Phi_{eff} = \Phi_{clay}(0)[1 - V_{silt}(Z)]\exp[-aP_{pore}(Z)],$$

wherein  $a = \frac{b}{(\rho_b - \rho_w)g}$  and

$b$  = compaction coefficient at depth of interest

$\rho_b$  = density of shale

$\rho_w$  = density of pore fluid

$g$  = gravitational acceleration,  $9.81 \text{ ms}^{-2}$

$\Phi_{eff}$  = effective porosity

$\Phi_{clay}$  = clay porosity at zero depth of burial

$V_{silt}$  = volume of non-clay mineral (silt) at depth of interest.

- 2 A method as claimed in claim 1, wherein the formation strength (FS) is derived from measurements of downhole bit torque (TOR) and downhole weight on bit (WOB) and where said formation strength is corrected for the effects of bit wear.



- 3 A method as claimed in claim 1 or 2, wherein

$$FS = FS_{ma} \left( 1 - \frac{V_{cl}}{V_{clzero}} - \frac{\Phi_{clay}}{\Phi_{clayzero}} \right)$$

where  $FS$  is formation strength,  $FS_{ma}$  is the formation strength of the non-clay mineral,  $V_{cl}$  is the volume of wet clay in the formation,  $\Phi_{clay}$  is the clay porosity, and the quantities with 'zero' subscripts are the values of the parameters at which the formation strength falls to zero.

- 4 A method as claimed in any preceding claim, wherein

$$GR = \sum_i V_i GR_i$$

where  $GR$  is total gamma-ray response,  $V_i$  is the volume fraction of mineral  $i$  in the rock, and  $GR_i$  is the gamma-ray response of that mineral in the absence of any others.

- 5 A method as claimed in any preceding claim, wherein

$$\frac{1}{\rho_{shale}} = \sigma_{shale} = \sigma_{fluid} \Phi_{clay}^m (1 - V_{silt})^{1.5}$$

where  $\rho_{shale}$  is shale resistivity,  $\sigma_{shale}$  is shale conductivity,  $\sigma_{fluid}$  is the pore fluid conductivity and  $m$  is the power-law exponent.

- 6 A method as claimed in claim 5, wherein, for a temperature ( $T$ ),

$$\sigma_{fluid}(T) = \sigma_{fluid}(T_0) \cdot \exp - \frac{E_a}{R} \left( \frac{1}{T} - \frac{1}{T_0} \right)$$

where  $\sigma_{fluid}(T_0)$  is the pore fluid conductivity at a temperature  $T_0$ ,  $E_a$  is an activation energy term and  $R$  is the gas constant.

- 7 A method as claimed in claim 5 or 6, wherein the power law exponent  $n$  is obtained from a cross-plot of

$$\log \frac{\sigma_{shale}}{\sigma_{fluid} \cdot (1 - V_{silt})^{1.5}} \text{ against } \log \Phi_{clay}$$

- 8 A method as claimed in any preceding claim further including measurement of one or more of neutron porosity, gamma ray density, sonic travel time deep induction resistivity and resistivity at bit.

- 9 A method as claimed in any preceding claim, wherein  $FS$  is derived as a function of rate of bit rotation, bit efficiency, gouging component of bit torque, rate of penetration, bit diameter and drilling mud weight.

- 10 A method of determining the volumetric composition of a shale comprising relating the effective porosity  $\Phi_{eff}$  of the shale to the porosity of 100% clay at the pressure of interest  $\Phi_{clay}$  according to the relationship:

$$\Phi_{eff} = \Phi_{clay}(1 - V_{silt})$$

wherein  $V_{silt}$  is the volume fraction of non-clay mineral and measuring the resistivity  $RES$  of the shale which is interpreted according to the relationship:

$$\frac{1}{\rho_{shale}} = \sigma_{shale} = \sigma_{fluid} \Phi_{clay}^m (1 - V_{silt})^{1.5}$$

wherein  $\rho_{shale}$  is the shale resistivity,  $\sigma_{shale}$  is shale conductivity,  $\sigma_{fluid}$  is the pore fluid conductivity and  $m$  is the power law exponent.

Patents Act 1977  
 Examiner's report to the Comptroller under  
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Databases (see over)

(i) UK Patent Office

(ii) ONLINE DATABASES: WPI

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8 FEBRUARY 1993

Documents considered relevant following a search in respect of claims 1-9

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A	US 4949575 (RASMUS)	
A	EP 0339752 A1 (ANADRILL) (equivalent to US 4833914)	

Category	Identity of document and relevant passages 	Relevant to claim(s)

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